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Lead Zirconate Titanate Acoustic Energy Harvesters Utilizing Different Polarizations on Diaphragm

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Abstract

This paper presents improved power generation performances of a PZT microelectromechanical systems (MEMS) acoustic energy harvester having dual top electrodes to utilize different polarizations of charges on the surface of a vibrating PZT diaphragm. The PZT acoustic energy harvester had a diaphragm with a diameter of 2 mm consisting of Al(0.1 μm)/PZT(1 μm)/Pt(0.1 μm)/Ti(0.1 μm)/SiO_2(1.5 μm). The top Al electrodes independently cover the peripheral surface and the central surface of the PZT diaphragm. The peripheral energy harvester generated a power of 5.28×10^{-11} W, and the central energy harvester generated a power of 4.25×10^{-11} W under the sound pressure level of 100 dB (0.01 W/m^2) at the first resonance frequency of 4.92 kHz. A connected energy harvester was also defined between the peripheral electrode and the central electrode. The total power generated by the connected harvesters was 8.28×10^{-11} W that corresponds to the power density of 20.7 $\mu W/m^2$. The device exhibited nearly two times larger power than the other devices with similar diaphragm areas.

Keywords: Acoustic energy harvester; PZT; Polarizations; Diaphragm

1. Introduction

Horowitz *et al.* have recently reported on a MEMS acoustic energy harvester that contains a PZT piezoelectric film as a diaphragm [1]. They claimed that their energy harvester with the PZT (0.27 μm thick) diaphragm with the diameter of 2.4 mm exhibited the power density of 0.34 $\mu W/cm^2$ at 149 dB sound pressure level (SPL) under the first-resonance vibration mode. The reason for measuring the energy harvester at such a high sound pressure level is the need for health monitoring systems in aircrafts where noises from engines are extremely high and wireless intelligent sensor systems are needed.

Shinoda *et al.* [2] fabricated PZT energy harvesters with similar sizes to those of Horowitz *et al.*, compared the performances of their energy harvesters with those of Horowitz *et al*. at 100 dB SPL, and reported that higher generated power could be realized by vibrating PZT diaphragms at the third-resonance frequency. Kimura *et al.* reported that PZT acoustic harvesters with non-wet electrode fabrication processes exhibited further improved power density at the first resonance [3]. However, these

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previous reports on the PZT acoustic energy harvesters did not consider to utilize the different polarity charges in the central part and the peripheral part of the diaphragms.

In this paper, we report on further improved performances of PZT acoustic energy harvesters that utilize different charge polarizations at the peripheral part and the central part of a PZT diaphragm at the first-resonance vibration.

2. Device Structure

Figure 1(a) shows the top view of the PZT energy harvester investigated here. The two top Al electrodes cover the peripheral area and the central area of the PZT diaphragm, respectively. The schematic cross-section of the energy harvester is shown in Fig. 1(b). A piezoelectric capacitor with the diaphragm structure of Al (0.1 µm)/PZT (1 µm)/Pt (0.1 µm)/Ti (0.1 µm) was formed on 1.5-µm-thick SiO_2. The cavity of the diameter of 2.0 mm was fabricated on a 300-µm-thick silicon wafer. When sound pressure is applied from above the device, the diaphragm vibrates, resulting in the deflection of the diaphragm. The deflected PZT capacitor generates a voltage difference between the two electrodes of Al and Pt/Ti owing to the polarization of PZT. In case of exciting the first resonance, the generated charge polarizations were different between the peripheral part and the central part as schematically shown in Fig. 1(c). This way, the dual top electrode dimensions were determined to utilize the different charge polarizations. Therefore, the independent top electrodes that covered the peripheral area and the central area to form the independent two energy harvesters were fabricated as illustrated in Fig. 1(d). The two energy harvesters were defined between the peripheral electrode and the common electrode, and the central electrode and the common electrode. A connected energy harvester was also defined between the two top electrodes. The detailed fabrication conditions have been already reported [2,3].

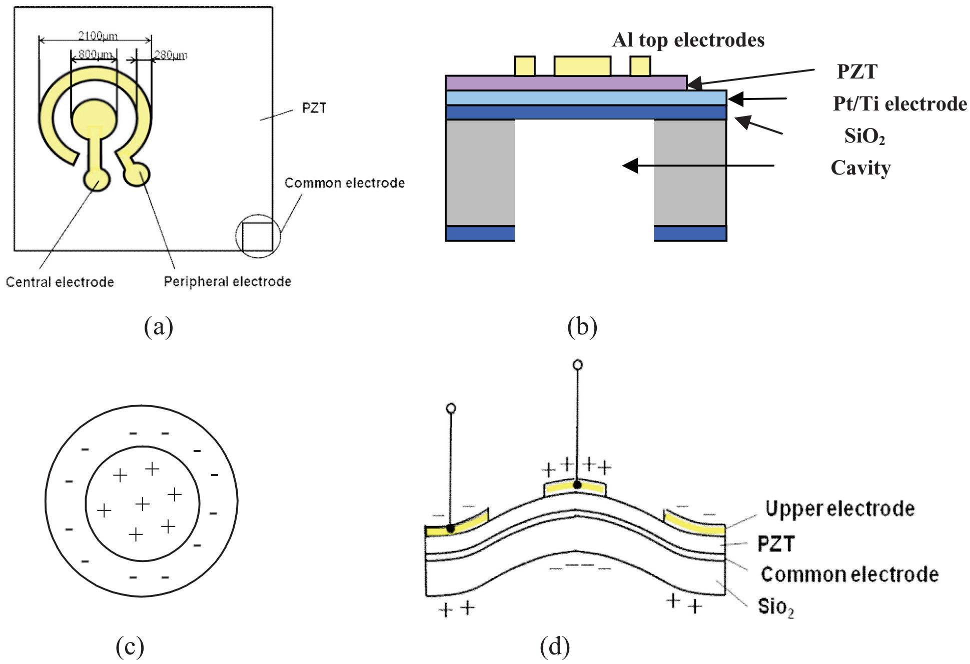

Fig. 1 Structure of PZT energy harvester; (a) top view, (b) Schematic cross section, (c) expected charge distribution, and (d) concept of connected energy harvester.

The resonance frequencies under a sound pressure of 100 dB SPL (0.01 W/m^2) were measured using the characterization system described in previous reports [2,3]. In order to measure the resonance frequency of the energy harvester, an amplifier with a gain of 10,000 was connected to amplify the output voltage signals from the energy harvester. In the case of measuring the generated power, a resistance was connected to the energy harvester, and the voltage between the two terminals of the load resister was monitored using an oscilloscope.

3. Results and Discussion

Figure 2 compares the frequency dependencies of the output voltages for the peripheral device and the central device under the sound pressure level of 100 dB. The output voltage, E was determined by measuring the open-circuit voltage between the two electrodes of the energy harvesters. A sharp resonance for the first resonance for the peripheral device and the central device were observed at 4.29 kHz, which was also suggested by the vibration analysis using the finite element method. The frequency dependence of a device with the same diaphragm diameter but with the circular-shaped top electrode covering whole surface of the diaphragm was also compared as a reference [3].

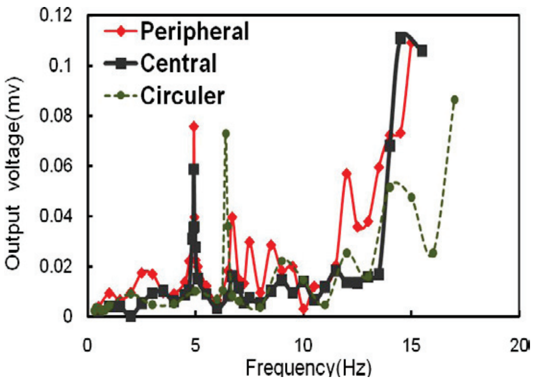

Fig. 2 Frequency dependence of output voltage.

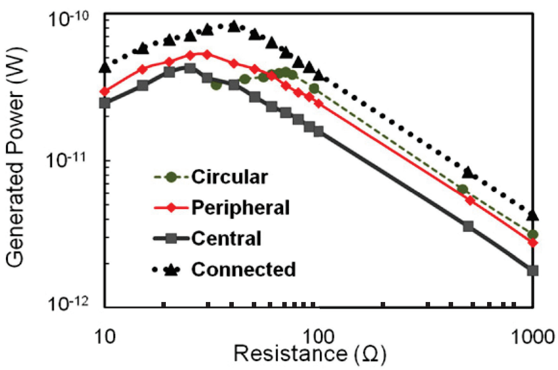

Fig. 3 Load resistance dependence of generated power

Figure 3 compares the load resistance dependences of the PZT energy harvesters of the peripheral device, the central device, the connected device, and the circular device of Kimura *et al.* [3] that covered the whole surface of the PZT diaphragm. The sound pressure of approximately 100 dB at the first-resonance frequency, 4.92 kHz was irradiated. The effective electric power delivered to the load resistance, R, was calculated from the measured voltage amplitude V using the relationship $P = V^2/2R$. The maximum power delivered to the load was derived when the load resistance was approximately 25-30 Ω. The connected device generated the largest power. Note that the powers generated by the peripheral device and the central devices were larger than that generated by the Kimura's device with the same dimension possibly owing to utilizing the polarizations of different polarities and the reduced harvester capacitance.

Table I shows the comparison of the performances of the PZT power generators prepared by Horowitz *et al.* [1], Shinoda *et al.* [2], Kimura *et al.* [3] and in this work. The energy harvesters of this research utilized the both of the charges at the peripheral and the central parts of the diaphragm. Thus, nearly double power was generated at the same energy harvester area.

Table 1 Comparison of performances of various acoustic energy harvesters

	Diaphragm Diameter (mm)	Resonance Frequency (Hz)	Generated Power (W)	Power density ($\mu W/m^2$)	Resistance at maximum power (ohm)
S. B. Horowitz et al [1]	2.4	13568	$6.0x10^{-12}$	1.0	1000
	3.6	5232	$7.0x10^{-13}$	0.054	1000
S. Shinoda et al. [2]	1.5	24020	$1.1x10^{-11}$	4.9	550
	2.0	18020	$5.1x10^{-12}$	1.3	550
Kimura et al. [3]	1.2	16700	$1.4x10^{-10}$	98	75
	2.0	6400	$4.0x10^{-11}$	10	70
This work	2.0 Outer	4920	$4.2x10^{-11}$	10.5	30
	2.0 Inner	4920	$5.28x10^{-11}$	13.2	25
	2.0 Connected	4920	$8.28x10^{-11}$	20.7	25

Conclusion

This paper presented improved power generation performances of a PZT microelectromechanical systems (MEMS) acoustic energy harvester having dual top electrodes to utilize the different polarizations of charges on the surface of a vibrating PZT diaphragm. The PZT acoustic energy harvester had a diaphragm with a diameter of 2 mm consisting of Al(0.1 μm)/PZT(1 μm)/Pt(0.1 μm)/Ti(0.1 μm)/ SiO_2(1.5 μm). The top Al electrodes independently cover the peripheral surface and the central surface of the PZT diaphragm. The peripheral energy harvester generated a power of $5.28x10^{-11}$ W, and the central energy harvester generated a power of $4.25x10^{-11}$ W under the sound pressure level of 100 dB (0.01 W/m^2) at 4.92 kHz. A connected energy harvester was also defined between the peripheral electrode and the central electrode. The total power generated by the connected harvesters was $8.28x10^{-11}$ W that corresponds to the power density of 20.7 $\mu W/m^2$. The device exhibited nearly two times larger power than the other devices with similar diaphragm areas.

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